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Article

On Producing Long-Lived Spin Polarized Metastable Atoms—Feasibility of Storing Electric Energy †

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† Dedicated to Miron Amusia.

Abstract: We describe a method of producing long-lived multiply excited spin polarized atoms or ions, the decay of which is strongly delayed or even blocked by intra-ionic magnetic stabilization. Special configurations with huge internal magnetic fields capture only spin polarized electrons in collisions with spin aligned atomic hydrogen gas targets. It is expected that the spin aligned configuration yields an extremely high internal magnetic field which will effectively block spin flip transitions. By this the lifetime of inner shell vacancies is expected to strongly increase.

Keywords: spin-polarized atoms; highly charged ions; energy storage

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Over thirty years ago, Miron Amusia was a frequent visitor to our institute at Frankfurt University. The actual reason for this was that at the time his granddaughter was staying in nearby Wiesbaden. Miron made use of the opportunity of seeing her to visit us at our Frankfurt institute and discuss interesting physics problems. One of them was ball lightning [1]. Miron made mention of research that was going on before 1990 in the then Soviet Union on the question of storing energy in light ball matter. Therefore, the question of the nature of light ball matter was intensively discussed.

The onset was somewhat similar to this: ball lightning occurs in thunderstorms in normal air. Characteristic for it is that it is a plasma-like object. Its size is about that of a ball of 50 cm in diameter, it emits light for about 30 s after creation, and it moves rotating (Figure 1). To account for the 30 s half-life of light emission, the emitting states in the corresponding atoms or ions would have to be metastable. The rotation of the light ball means that its angular momentum probably is the sum of the angular momenta of space quantized atoms, similar to what occurs in the Einstein-de Hass effect [2]. Since air consists mainly of N_2, we were speculating that a special metastable spin polarized configuration of N_2* or N* produced in a lightening event might be causing the ball-lightning effect. An N* configuration could possibly be ($1s^2$, $2s^1$, $2p^3$, $3s^1$), where a 2s electron is excited into the 3s shell by the strongly varying magnetic field in the lightning flash. In the process the excited electron makes a spin flip. Thus, all the electrons in the 2s, 2p, and 3s shells have the same spin orientation (Figure 2). The $1s^2$ remains a closed shell and the electrons in 3s can only decay via spin flip into the 2s state, and the transition is strongly delayed.

Excited atoms and ions with inner shell vacancies have been explored in slow ion-atom collisions. Many groups investigated their formation and decay [3–8]. It is well known that inner shell vacancies of multiply excited hollow atoms or ions decay mostly within fractions of a picosecond by Auger or X-ray emission, when the electrons undergo transitions without spin-flip. In some experiments metastable configurations have been observed with a delayed decay in the nanosecond regime. In nature and also under laboratory conditions so far, no evidence has been found that long-lived (millisecond or longer) metastable multiply excited ionic or atomic systems are created in such collisions. To our knowledge, in all these experiments the spin configuration was not known. Only in some instances of highly ionized few-electron ions the spin configuration was known. Here only one electron is excited, and its decay is highly forbidden, i.e., the state can only decay by magnetic dipole or two-photon transition or spin-flip. Such ionic configurations have lifetimes of the order of microseconds or even longer. Ninomiya et al. [9] found evidence for longer living “metastable hollow atoms” that were formed by penetration of highly charged ions through very narrow channels in thin films. Therefore, to create metastable configurations with multiple vacancies and with long lifetimes one must be able to create ionic configurations in a controlled way where the spin orientation of the electrons can be manipulated.

Figure 1. A 1901 illustration of ball lightning (Ball lightning—Wikipedia).

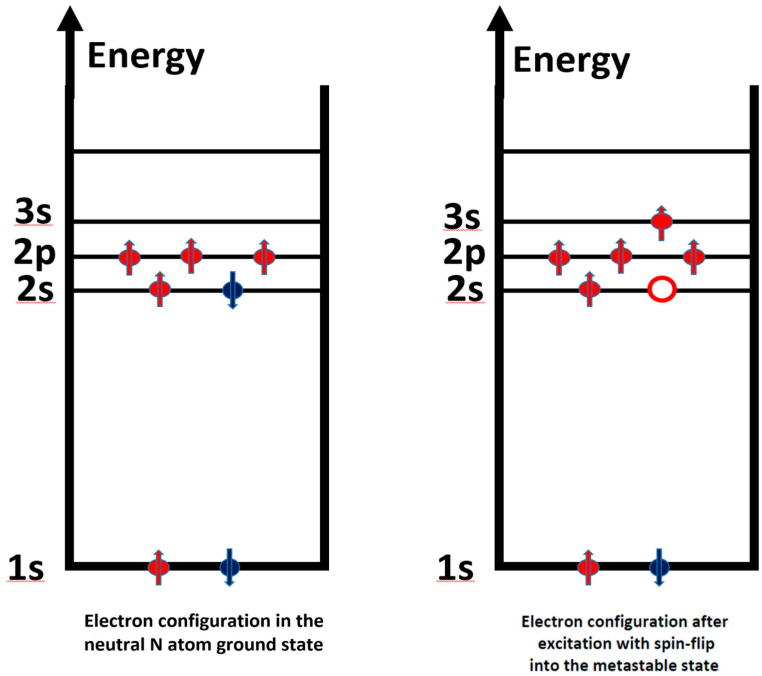
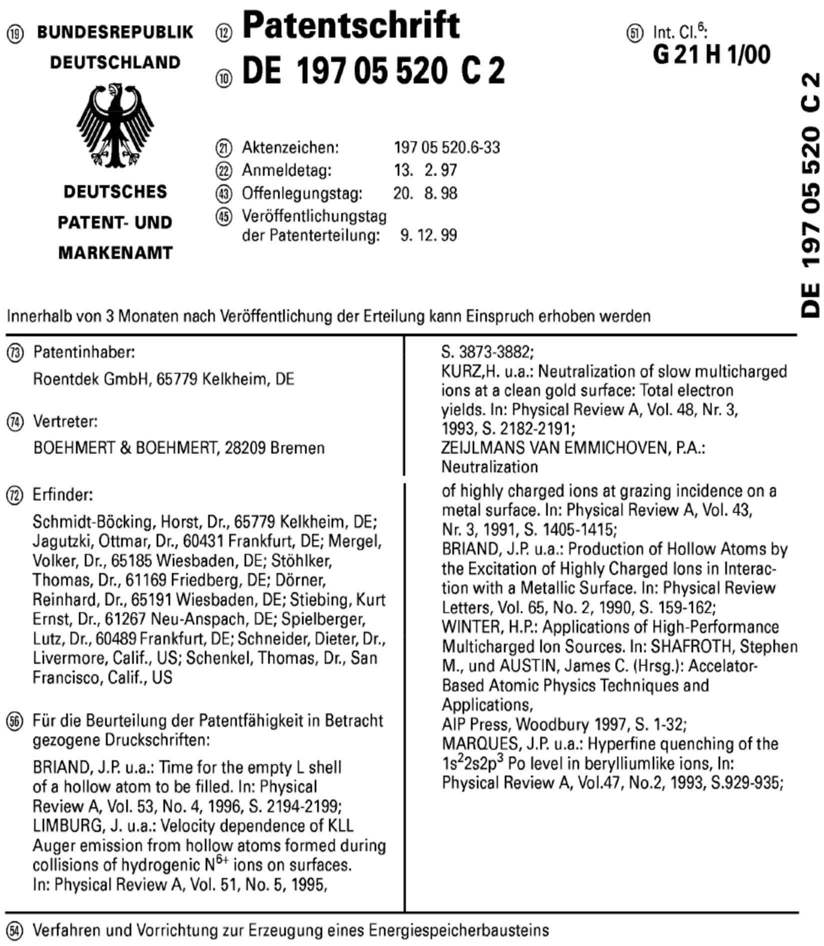


Figure 2. N-atom configuration, left in the ground state and right in the excited state. “Red” electrons are in spin-up state, blue ones in spin-down state. The open circle indicates the vacancy state.

If in a multiple-capture process all captured electrons have parallel spins, the energy barrier for a spin flip should strongly increase. In this case it might be possible to block or delay spin flip transitions due to the very strong internal magnetic field. The multiple-capture process, however, must be fast enough (in the order of a microsecond) that, until the formation of the very high internal magnetic field, the highly excited ion has no time to decay. Due to such a strong internal magnetic field and the blocking of spin-flip transitions caused by it, even in special neutral atoms the lifetime of inner-shell vacancies might be strongly enhanced and may last up to milliseconds or even longer. For such special ionic configurations, an internal magnetic field strength much stronger than achievable up to now in laboratories (≥90 Tesla [10]) may exist.

For obtaining qualitative information on the lifetime of such metastable subjects we contacted experts in calculating the configuration of multiply excited ions or atoms [11]. However, their theoretical approach was not capable of calculating transitions in extremely strong inner atomic magnetic fields. They also were not able to calculate the magnetic field-strength, e.g., for an S = 9 configuration. They told us, however, that no spin-flip should occur when the magnetic field is infinitely large. The theorists thought it is not likely that such configurations would have a lifetime sufficiently long for applications in everyday life, e.g., for efficiently storing energy by use of long living inner shell vacancies in so-called spin-polarized matter. However, nobody excluded that it might be possible nevertheless to produce such matter.

Therefore, this short letter is also written to stimulate the interest of theorists in such spin-polarized configurations. Since to our knowledge no data on the lifetime of such spin-polarized metastable states and the strength of the inner-atom magnetic field is available in literature, we will only outline an experimental route of how to produce such atoms with very high S value in the laboratory. It may be noted in passing that the here presented scheme of producing spin-polarized matter has been patented by the German Patent Office [12] (Figure 3).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(54) Verfahren und Vorrichtung zur Erzeugung eines Energiespeicherbausteins

Figure 3. German patent on formation of spin-polarized atoms for energy storage [12].

Figure 4 schematically shows the experimental arrangement for producing spin-polarized neutral-atom beams. The apparatus consists of three experimental sections: highly charged ions in a special charge state are produced in an Electron Cyclotron Resonance ion source (ECR) [13]. With modern ion source techniques nearly any kind of ions in any charge state can be produced. Present ECR ion sources or EBIS or EBIT devices can produce high intensity low energy beams of highly charged ions.

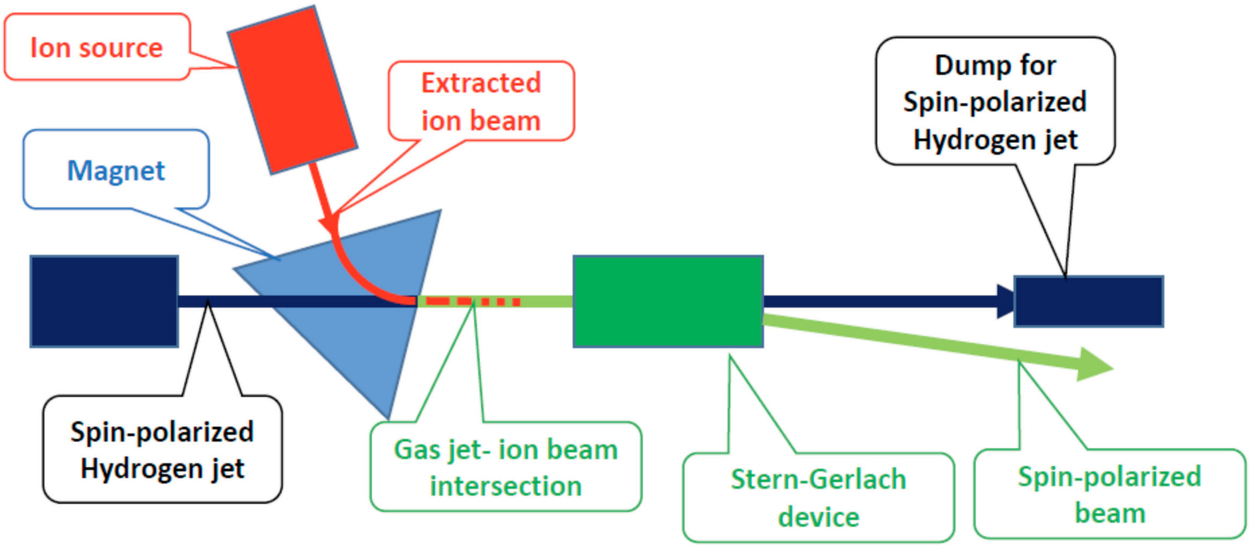

Figure 4. Scheme of experimental set-up to create spin-polarized neutral atoms (see text).

The magnetically selected beam penetrates a nearly completely spin-polarized hydrogen gas-jet and thereby captures within a few microseconds many spin-polarized electrons for getting neutralized. To our knowledge spin-polarized H targets (supersonic jets) with an 80% degree of polarization are extant [14]. Since this kind of target provides a very high target thickness, we believe that the degree of polarization can be enhanced in a second Stern-Gerlach device, with loss of target thickness, however. The non-neutralized beam components are magnetically deflected behind the gas target in the Stern-Gerlach apparatus and removed. The neutralized beam is spin-state selected in the same Stern-Gerlach device [15,16]. In this way a neutral spin-polarized atomic beam is generated: thus, a larger fraction of the highly spin-polarized atoms have possibly the same spin-polarized configuration.

As an example, we consider the production of spin-polarized Kr atoms, starting with the extraction of Kr^{13+} ions from an ECR ion source, having 23 electrons in their ionic shells. This ion charge state is chosen because it has a high internal magnetic field. This is due to the ionic electron-configuration being such that all lower shells ($1s^2$, $2s^2$, $2p^6$, $3s^2$, $3p^6$) are filled and the 3d shell is half filled, $3d^5$. According to Hund's rule [17,18], in this configuration the Kr^{13+} ions should have a total L value of zero, the total S value should be maximum, S = 2.5.

The selected ion beam is injected in a spin-polarized hydrogen-gas target-jet (Figure 4). The intersection of the ion beam and the hydrogen jet is arranged thus that both the ion beam and the atoms in the jet move in parallel (for about 10 cm), improving by their larger intersection length the capture probability. After capturing another 13 spin-polarized electrons, a measurable fraction of the neutral Kr atoms should be in the S state of S = 9.

The neutralized Kr beam is injected in another Stern-Gerlach device which separates the Kr atoms according to their S value and to the orientation of the total spin. Out of the second Stern-Gerlach device several Kr beams emerge, being separated according to their spin polarization.

It may even be possible to produce in such a set-up neutral uranium being in a S = 37 state. One would start with extracting U^{69+} ions from an ion source (ground state configuration: $1s^2$, $2s^2$, $2p^6$, $3s^2$, $3p^6$, $3d^5$) (Figure 5). When these ions capture 69 spin-oriented electrons in a spin-polarized hydrogen-jet all higher states (higher than 3d) can be filled with electrons of the same spin direction in the deepest allowed states. In the most favorable case one might obtain even a ($1s^2$, $2s^2$, $2p^6$, $3s^2$, $3p^6$, $4s^1$, 4p, $4d^5$, $4f^7$, $5s^1$, $5p^3$, $5d^5$, $5f^7$, $5g^9$, $6s^1$, $6p^3$, $6d^5$, $6f^7$, $7s^1$, $7p^3$, $7d^5$, $8s^1$, $8p^2$) configuration. The S value of this configuration would be S = 37.

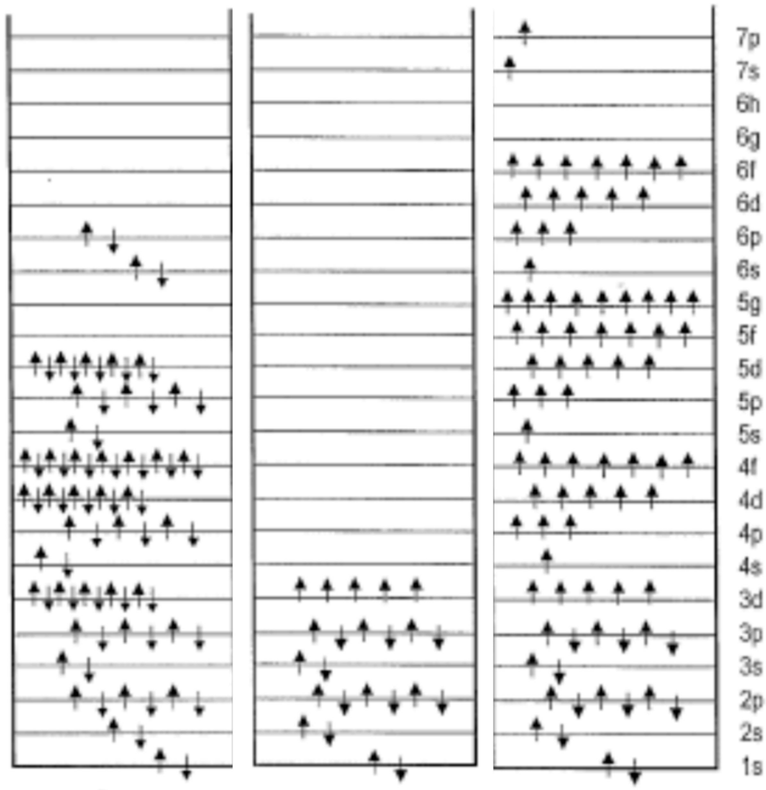

Figure 5. Electron shell configurations. Left, for the neutral uranium atom, middle, for the uranium 69+ ion, right, for a neutral uranium atom after capture of 69 spin-orientated electrons [19] (see text).

Extremely magnetic atoms of this kind may show many new quantum features. The magnetic field might be so strong that, for instance, in Kr atomic bonding proceeds via magnetic forces. This would possibly provide matter with unexpected e-e- correlation features. In addition, the amount of energy stored in the empty states would be huge, because the states of different spin polarization in the atom are empty. For a single uranium atom, it might exceed 30 keV. This is 10,000 times more than a conventional electric battery can store. Whether this would be practically applicable is very unlikely, but who may know?

To conclude: the procedure outlined above of how to produce spin-polarized atoms in an unusual high spin state seems rather exotic. However, we believe that it should be possible, as discussed, to produce sufficiently many atoms of this kind for exploring the physics of such exotic spin-polarized quantum systems in the laboratory. Spin-polarized matter can open up new interesting fields in atomic and solid-state physics.

Without the stimulating discussions with Miron Amusia in Frankfurt more than 30 years ago, we would never have come in contact with the question of what ball- lightning matter might be. We have written this short letter to present the ideas Miron initiated. We think we owe to Miron Amusia the publication of these ideas. When Max Born tried to prevent Otto Stern from performing the Stern-Gerlach experiment because it seemed infeasible to him, Otto Stern replied: no experiment is as dumb as not to perform it.

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